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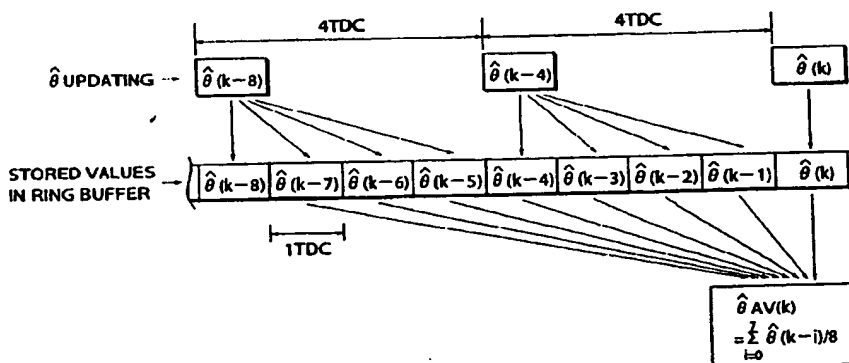
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(54) Air-fuel ratio control system for multi-cylinder internal combustion engines

(57) An air-fuel ratio control system for a multi-cylinder engine is provided. An air-fuel ratio sensor is arranged in an exhaust system of the engine for detecting an air-fuel ratio of a mixture supplied to the engine and for generating an output indicative of the air-fuel ratio of the mixture. An adaptive controller determines an amount of fuel to be supplied to the engine with a first predetermined repetition period in a manner such that the output from the air-fuel ratio sensor becomes equal to a desired value. An adaptive parameter-adjusting mechanism adjusts adaptive parameters used by the adaptive controller. In the adaptive parameter-adjusting

mechanism, the adaptive parameters are calculated with a second predetermined repetition period longer than the first predetermined repetition period, and output data indicative of results of the calculation is generated. Further, the output data indicative of results of the calculation is smoothed and output data indicative of the smoothed data is generated with a repetition period at least equal to the first predetermined repetition period. The adaptive controller uses the smoothed data as values of the adaptive parameters.

FIG.11



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Description

BACKGROUND OF THE INVENTION

5 Field of the Invention

[0001] This invention relates to an air-fuel ratio control system for multi-cylinder internal combustion engines, which controls an amount of fuel to be supplied to the engine by means of feedback control based on an adaptive control theory.

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Prior Art

[0002] Conventionally, an air-fuel ratio control system for internal combustion engines is known, e.g. from Japanese Laid-Open Patent Publication (Kokai) No. 8-232733, in which an adaptive parameter-adjusting mechanism calculates adaptive parameters and an adaptive controller carries out feedback control of the air-fuel ratio of a mixture supplied to the engine to a desired air-fuel ratio by using the adaptive parameters. In the known air-fuel ratio control system, an air-fuel ratio sensor arranged in the exhaust system of the engine detects the air-fuel ratio of the mixture and supplies a signal indicative of the detected air-fuel ratio to the adaptive controller, which in turn determines an amount of fuel to be supplied to the engine such that the detected air-fuel ratio becomes equal to a desired air-fuel ratio.

[0003] In the air-fuel ratio control system disclosed in the above publication, values of the adaptive parameters calculated in the past by the adaptive parameter-adjusting mechanism are averaged, and the adaptive parameter values thus averaged are used by the adaptive controller, so as to prevent the adaptive control from being adversely influenced by a particular cylinder when the adaptive control is carried out in a manner synchronous to the combustion cycle of the engine.

[0004] Further, if the calculation of a plurality of adaptive parameters is carried out with the same repetition period as a repetition period of calculation of the amount of fuel to be supplied to the engine, e.g. a repetition period of generation of TDC pulses, the amount of calculation increases to increase load on a CPU which calculates the adaptive parameters. To avoid this inconvenience, the repetition period $T\theta$ of calculation of the adaptive parameters is set longer than the repetition period TF of calculation of the amount of fuel to be supplied to the engine, e.g. to a period equal to $TF \times$ the number of cylinders, to thereby reduce the amount of calculation of the adaptive parameters to reduce the load on the CPU.

[0005] In the conventional air-fuel ratio control system, however, when the averaged adaptive parameter values are calculated by the adaptive parameter-adjusting mechanism with the repetition period $T\theta$ of calculation set longer than the repetition period TF with which the adaptive controller calculates the amount of fuel supplied to the engine, a plurality of values of each adaptive parameter calculated at the repetition period $T\theta$ at different times are averaged and the averaged parameter values are used by the adaptive controller. This brings about the following problem:

[0006] The adaptive parameter values used by the adaptive controller each contain a component of a particular frequency corresponding to the reciprocal of the repetition period $T\theta$ and harmonic components of the same, whereas the output from the air-fuel ratio sensor does not contain components corresponding, especially, to the harmonic components due to the low-pass characteristic of the sensor. This increases an identification error in the adaptive parameters, resulting in divergence of the adaptive control.

[0007] More specifically, the adaptive parameter-adjusting mechanism is capable of carrying out accurate identification of the adaptive parameters on condition that frequency components of output data (= the adaptive parameters) from the adjusting mechanism are fed back as input data to the adjusting mechanism without being lost after being transformed through a controlled variable (= the amount of fuel to be supplied to the engine), a plant to be controlled (= the multi-cylinder engine), and a plant output sensor (= the air-fuel ratio sensor). However, in actuality the components corresponding to the harmonic components are lost due to the low-pass characteristic of the air-fuel ratio sensor and not fed back to the adaptive parameter-adjusting mechanism. This causes the above-mentioned increase in the identification error.

[0008] Further, since the repetition period $T\theta$ of calculation of the adaptive parameters is set longer than the repetition period TF of calculation of the amount of fuel to be supplied to the engine, the calculated adaptive parameter values cannot be quickly changed in response to changes in operating conditions of the engine without delay, which hinders the amount of fuel to be supplied to the engine from being quickly converged to a desired value. This inconvenience becomes more marked through averaging of adaptive parameters since the averaged values of the adaptive parameters are applied to the calculation of the amount of fuel with the repetition period $T\theta$.

SUMMARY OF THE INVENTION

[0009] It is an object of the present invention to provide an air-fuel ratio control system for a multi-cylinder internal combustion engine, which is capable of continuing stable adaptive control even when the adaptive parameters are calculated with a repetition period longer than the repetition period of calculation of an amount of fuel supplied to the engine.

[0010] To attain the above object, the invention provides an air-fuel ratio control system for a multi-cylinder engine having a plurality of cylinders and an exhaust system connected to the cylinders, including air-fuel ratio-detecting means arranged in the exhaust system for detecting an air-fuel ratio of a mixture supplied to the engine and for generating an output indicative of the air-fuel ratio of the mixture, an adaptive controller for determining an amount of fuel to be supplied to the engine with a first predetermined repetition period in a manner such that the output from the air-fuel ratio-detecting means becomes equal to a desired value, and adaptive parameter-adjusting means for adjusting adaptive parameters used by the adaptive controller.

[0011] The air-fuel control system according to the invention is characterized in that the adaptive parameter-adjusting means comprises:

adaptive parameter-calculating means for calculating the adaptive parameters with a second predetermined repetition period longer than the first predetermined repetition period and for generating output data indicative of results of the calculation; and

smoothing means for smoothing the output data from the adaptive parameter-calculating means and for generating output data indicative of the smoothed data with a repetition period at least equal to the first predetermined repetition period;

wherein the adaptive controller uses the smoothed data generated from the smoothing means as values of the adaptive parameters.

[0012] Preferably, the smoothing means stores the output data from the adaptive parameter-calculating means with the first predetermined repetition period, and carries out the smoothing by using a predetermined number of stored values of the output data from the adaptive parameter-calculating means.

[0013] More preferably, the smoothing comprises calculating moving average values of the output data from the adaptive parameter-calculating means.

[0014] Further preferably, the adaptive parameter-calculating means includes storage means for sequentially storing values of each of the adaptive parameters with the first predetermined repetition period, and updating means for sequentially updating each of the values of the each of the adaptive parameters stored in the storage means to an identical value with the second predetermined repetition period, the smoothing means calculating moving average values of the values of the each of the adaptive parameters sequentially updated to the identical value.

[0015] Also preferably, the smoothing means includes a ring buffer for storing the output data from the adaptive parameter-calculating means.

[0016] Preferably, the second predetermined repetition period is set to q times the first predetermined repetition period (q is an integer equal to or larger than 2), the predetermined number being equal to or larger than the q .

[0017] Further preferably, the q depends upon a particular frequency.

[0018] More preferably, assuming that a number of the cylinders is j , the second predetermined repetition period is set to j times the first predetermined repetition period, the predetermined number being equal to t times the number j of the cylinders (t is an integer equal to or larger than 1).

[0019] The above and other objects, features, and advantages of the invention will become more apparent from the following detailed description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020]

Fig. 1 is a block diagram showing the arrangement of a multi-cylinder internal combustion engine and an air-fuel ratio control system therefor, according to an embodiment of the invention;

Fig. 2 is a block diagram useful in explaining a manner of controlling the air-fuel ratio of a mixture supplied to the engine appearing in Fig. 1;

Fig. 3 is a flowchart showing a main routine for calculating an adaptive control correction coefficient KSTR in response to an output from a LAF sensor appearing in Fig. 1;

Fig. 4 is a flowchart showing a subroutine for carrying out a LAF feedback control region-determining process, which is executed at a step S6 in Fig. 3;

Fig. 5 is a block diagram useful in explaining a manner of calculating the adaptive control correction coefficient KSTR;

Figs. 6A and 6B are diagrams useful in explaining improved control performance, exhibited by a control method employed in the embodiment;

Fig. 7A is a block diagram showing an adaptive parameter vector-calculating section for calculating an adaptive parameter vector;

Fig. 7B is a block diagram showing a variation of the adaptive parameter vector-calculating section;

Fig. 8A and 8B are diagrams useful for explaining characteristics of a filter appearing in Fig. 7A;

Fig. 8C is a diagram useful for explaining characteristics of a filter appearing in Fig. 7B;

Fig. 9 is a flowchart showing a subroutine for calculating the adaptive control correction coefficient KSTR;

Fig. 10 is a flowchart showing a subroutine for calculating adaptive parameters;

Fig. 11 is a diagram which is useful in explaining a method of calculating moving average values of the adaptive parameters; and

Fig. 12 is a diagram showing changes in adaptive parameter values and their moving average values.

DETAILED DESCRIPTION

[0021] The invention will now be described in detail with reference to the drawings showing an embodiment thereof.

[0022] Fig. 1 schematically shows the whole arrangement of a multi-cylinder internal combustion engine (hereinafter simply referred to as the engine) and a control system therefor, according to an embodiment of the invention.

[0023] In Fig. 1, reference numeral 1 designates a four-cylinder type internal combustion engine. The engine 1 has an intake pipe 2 having a manifold part (intake manifold) 11 directly connected to the combustion chamber of each cylinder. A throttle valve 3 is arranged in the intake pipe 2 at a location upstream of the manifold part 11. A throttle valve opening (θTH) sensor 4 is connected to the throttle valve 3, for generating an electric signal indicative of the sensed throttle valve opening θTH and supplying the same to an electronic control unit (hereinafter referred to as the ECU) 5. The intake pipe 2 is provided with an auxiliary air passage 6 bypassing the throttle valve 3, and an auxiliary air amount control valve (electromagnetic valve) 7 is arranged across the auxiliary air passage 6. The auxiliary air amount control valve 7 is electrically connected to the ECU 5 to have an amount of opening thereof controlled by a signal therefrom. An intake air temperature (TA) sensor 8 is inserted into the intake pipe 2 at a location upstream of the throttle valve 3, for supplying an electric signal indicative of the sensed intake air temperature TA to the ECU 5. The intake pipe 2 has a swelled portion 9 as a chamber interposed between the throttle valve 3 and the intake manifold 11. An intake pipe absolute pressure (PBA) sensor 10 is arranged in the chamber 9, for supplying a signal indicative of the sensed intake pipe absolute pressure PBA to the ECU 5. An engine coolant temperature (TW) sensor 13, which may be formed of a thermistor or the like, is mounted in the cylinder block of the engine 1 filled with an engine coolant, for supplying an electric signal indicative of the sensed engine coolant temperature TW to the ECU 5. A crank angle position sensor 14 for detecting the rotational angle of a crankshaft, not shown, of the engine 1 is electrically connected to the ECU 5 for supplying an electric signal indicative of the sensed rotational angle of the crankshaft to the ECU 5. The crank angle position sensor 14 is comprised of a cylinder-discriminating sensor, a TDC sensor, and a CRK sensor. The cylinder-discriminating sensor generates a signal pulse (hereinafter referred to as a CYL signal pulse) at a predetermined crank angle of a particular cylinder of the engine 1, the TDC sensor generates a signal pulse at each of predetermined crank angles (e.g. whenever the crankshaft rotates through 180 degrees when the engine is of the 4-cylinder type) which each correspond to a predetermined crank angle before a top dead point (TDC) of each cylinder corresponding to the start of the suction stroke of the cylinder, and the CRK sensor generates a signal pulse at each of predetermined crank angles (e.g. whenever the crankshaft rotates through 30 degrees) with a predetermined repetition period shorter than the repetition period of TDC signal pulses. The CYL signal pulse, TDC signal pulse, and CRK signal pulse are supplied to the ECU 5, which are used for controlling various kinds of timing, such as fuel injection timing and ignition timing, and for detecting the engine rotational speed NE.

[0024] Fuel injection valves 12 are inserted into the intake manifold 11 for respective cylinders at locations slightly upstream of intake valves, not shown. The fuel injection valves 12 are connected to a fuel pump, not shown, and electrically connected to the ECU 5 to have the fuel injection timing and fuel injection periods (valve opening periods) thereof controlled by signals therefrom. Spark plugs, not shown, of the engine 1 are also electrically connected to the ECU 5 to have the ignition timing θIG thereof controlled by signals therefrom.

[0025] An exhaust pipe 16 of the engine has a manifold part (exhaust manifold) 15 directly connected to the combustion chambers of the cylinders of the engine 1. A linear output air-fuel ratio sensor (hereinafter referred to as the LAF sensor) 17 is arranged in a confluent portion of the exhaust pipe 16 at a location immediately downstream of the exhaust manifold 15. Further, a first three-way catalyst (immediate downstream three-way catalyst) 19 and a second three-way catalyst (bed-downstream three-way catalyst) 20 are arranged in the confluent portion of the exhaust pipe 16 at locations downstream of the LAF sensor 17, for purifying noxious components present in exhaust gases, such as HC,

CO, and NOx. An oxygen concentration sensor (hereinafter referred to as the O2 sensor) is inserted into the exhaust pipe 16 at a location intermediate between the three-way catalysts 19 and 20.

[0026] The LAF sensor 17 is electrically connected via a low-pass filter 22 to the ECU 5, for supplying the ECU 5 with an electric signal substantially proportional in value to the concentration of oxygen present in exhaust gases from the engine (i.e. the air-fuel ratio). The O2 sensor 18 has an output characteristic that output voltage thereof drastically changes when the air-fuel ratio of exhaust gases from the engine changes across a stoichiometric air-fuel ratio to deliver a high level signal when the mixture is richer than the stoichiometric air-fuel ratio, and a low level signal when the mixture is leaner than the same. The O2 sensor 18 is electrically connected via a low-pass filter 23 to the ECU 5 for supplying the ECU 5 with the high or low level signal. The low-pass filters 22 and 23 are provided for eliminating high frequency noise components, and influence thereof on the responsiveness of the air-fuel ratio control system is negligible.

[0027] The engine 1 includes a valve timing changeover mechanism 60 which changes valve timing of at least the intake valves out of the intake valves and exhaust valves, not shown, between a high speed valve timing suitable for operation of the engine in a high speed operating region thereof and a low speed valve timing suitable for operation of the engine in a low speed operating region thereof. The changeover of the valve timing includes not only timing of opening and closing of the valve but also changeover of the valve lift amount, and further, when the low speed valve timing is selected, one of the two intake valves is disabled, thereby ensuring stable combustion even when the air-fuel ratio of the mixture is controlled to a leaner value than the stoichiometric air-fuel ratio.

[0028] The valve timing changeover mechanism 60 changes the valve timing by means of hydraulic pressure, and an electromagnetic valve for changing the hydraulic pressure and a hydraulic pressure sensor, neither of which is shown, are electrically connected to the ECU 5. A signal indicative of the sensed hydraulic pressure is supplied to the ECU 5 which in turn controls the electromagnetic valve for changing the valve timing.

[0029] Further electrically connected to the ECU 5 is an atmospheric pressure (PA) sensor 21, for detecting atmospheric pressure PA, and supplying a signal indicative of the sensed atmospheric pressure PA to the ECU 5.

[0030] The ECU 5 is comprised of an input circuit having the functions of shaping the waveforms of input signals from various sensors including ones mentioned above, shifting the voltage levels of sensor output signals to a predetermined level, converting analog signals from analog-output sensors to digital signals, and so forth, a central processing unit (hereinafter referred to as the CPU), a memory circuit comprised of a ROM storing various operational programs which are executed by the CPU and various maps and tables, referred to hereinafter, and a RAM for storing results of calculations from the CPU, etc., and an output circuit which outputs driving signals to the fuel injection valves 12 and other electromagnetic valves, spark plugs, etc.

[0031] The ECU 5 operates in response to the above-mentioned signals from the sensors to determine operating conditions in which the engine 1 is operating, such as an air-fuel ratio feedback control region in which air-fuel ratio feedback control is carried out in response to outputs from the LAF sensor 17 and the O2 sensor 18, and air-fuel ratio open-loop control regions, and calculates, based upon the determined engine operating conditions, the fuel injection period TOUT over which the fuel injection valves 12 are to be opened, by using the following equation (1), to output signals for driving the fuel injection valves 12, based on results of the calculation:

$$TOUT = TIMF \times KTOTAL \times KCMDM \times KFB \quad (1)$$

where TIMF represents a basic value of the fuel injection amount TOUT, KTOTAL a correction coefficient, KCMDM a final desired air-fuel ratio coefficient, and KFB a feedback correction coefficient, respectively.

[0032] Fig. 2 is a block diagram useful in explaining the manner of calculating the fuel injection period TOUT by using the equation (1). With reference to the figure, an outline of the manner of calculating the fuel injection period TOUT according to the present embodiment will be described. It should be noted that in the present embodiment, the amount of fuel to be supplied to the engine is calculated, actually, in terms of a time period over which the fuel injection valve 6 is opened (fuel injection period), but in the present specification, the fuel injection period TOUT is referred to as the fuel injection amount or the fuel amount since the fuel injection period is equivalent to the amount of fuel injected or to be injected.

[0033] In Fig. 2, a block B1 calculates the basic fuel amount (basic value of the fuel injection amount) TIMF corresponding to an amount of intake air supplied to the engine 1. The basic fuel amount TIMF is basically set according to the engine rotational speed NE and the intake pipe absolute pressure PBA. However, it is preferred that a model representative of a part of the intake system extending from the throttle valve 3 to the combustion chambers of the engine 1 is prepared in advance, and a correction is made to the basic fuel amount TIMF in dependence on a delay of the flow of intake air obtained based on the model. In this preferred method, the throttle valve opening θ_{TH} and the atmospheric pressure PA are also used as additional parameters indicative of operating conditions of the engine.

[0034] Reference numerals B2 to B4 designate multiplying blocks, which multiply the basic fuel amount TIMF by respective parameter values input thereto, and deliver the product values. These blocks carry out the arithmetic opera-

$$\begin{aligned}\hat{\theta}^T(k) &= [b_0(k), r_1(k), \dots, r_{m+d-1}(k), s_0(k), \dots, s_{n-1}(k)] \\ &= [b_0(k), r_1(k), r_2(k), r_3(k), s_0(k)]\end{aligned}\quad (4)$$

$$\begin{aligned}\zeta^T(k) &= [u(k), \dots, u(k-m-d+1), y(k), \dots, y(k-n+1)] \\ &= [u(k), u(k-1), u(k-2), u(k-3), y(k)]\end{aligned}\quad (5)$$

[0052] The adaptive parameter vector $\hat{\theta}(k)$ is expressed by the following equation (6):

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \Gamma(k-1) \zeta(k-d) e^*(k) \quad (6)$$

where the symbols $\Gamma(k)$ and $e^*(k)$ represent a gain matrix and an identification error signal, respectively, and can be expressed by the following recurrence formulas (7) and (8):

$$\Gamma(k) = \frac{1}{\lambda_1(k)} \left[\Gamma(k-1) - \frac{\lambda_2(k) \Gamma(k-1) \zeta(k-d) \zeta^T(k-d) \Gamma(k-1)}{\lambda_1(k) + \lambda_2(k) \zeta^T(k-d) \Gamma(k-1) \zeta(k-d)} \right] \quad (7)$$

$$e^*(k) = \frac{(D(z^{-1})y(k) - \hat{\theta}^T(k-1)\zeta(k-d))}{1 + \zeta^T(k-d)\Gamma(k-1)\zeta(k-d)} \quad (8)$$

[0053] Further, it is possible to provide various specific algorithms depending upon set values of $\lambda_1(k)$ and $\lambda_2(k)$ in the equation (7). For example, if $\lambda_1(k) = 1$ and $\lambda_2(k) = \lambda$ ($0 < \lambda < 2$) hold, a progressively decreasing gain algorithm is provided (if $\lambda = 1$, the least square method), if $\lambda_1(k) = \lambda_1$ ($0 < \lambda_1 < 1$) and $\lambda_2(k) = \lambda_2$ ($0 < \lambda_2 < 2$) hold, a variable gain algorithm (if $\lambda_2 = 1$, the method of weighted least squares), and if $\lambda_1(k)/\lambda_2(k) = \alpha$ and if λ_3 is expressed by the following equation (9), $\lambda_1(k) = \lambda_3$ provides a fixed trace algorithm. Further, if $\lambda_1(k) = 1$ and $\lambda_2(k) = 0$ hold, a fixed gain algorithm is obtained. In this case, as is clear from the equation (6), $\Gamma(k) = \Gamma(k-1)$ holds, and hence $\Gamma(k) = \Gamma$ (fixed value) is obtained.

[0054] Further, $D(z^{-1})$ in the equation (8) is an asymptotically stable polynomial which can be defined by a system designer as desired to determine the convergence of the system. In the present embodiment, it is set to a value 1.0.

$$\lambda_3(k) = 1 - \frac{\|\Gamma(k-1)\zeta(k-d)\|^2}{\alpha + \zeta^T(k-d)\Gamma(k-1)\zeta(k-d)} \cdot \frac{1}{\text{tr}\Gamma(0)} \quad (9)$$

[0055] In the equation (9), $\text{tr}\Gamma(0)$ is a trace function of the matrix $\Gamma(0)$, and specifically, it is a sum (scalar) of diagonal components of the matrix $\Gamma(0)$.

[0056] The STR controller and the adaptive parameter-adjusting mechanism are arranged outside the fuel injection amount-calculating system, and operate to calculate the adaptive control correction coefficient $KSTR(k)$ such that the actual equivalent ratio $KACT(k+d)$ becomes equal to the desired equivalent ratio $KCMD(k)$ in an adaptive manner.

[0057] As shown in Fig. 5, the adaptive control correction coefficient $KSTR(k)$ and the actual equivalent ratio $KACT(k)$ are determined, which are input to the adaptive parameter-adjusting mechanism, where the adaptive parameter vector $\hat{\theta}(k)$ is calculated to be input to the STR controller. The STR controller is also supplied with the desired equivalent ratio $KCMD(k)$ and calculates the adaptive control correction coefficient $KSTR(k)$ such that the actual equivalent ratio $KACT(k+d)$ becomes equal to the desired equivalent ratio $KCMD(k)$, by using the following recurrence formula (10):

$$KSTR(k) = \frac{KCMD(k) - s_0 \times KACT(k) - r_1 \times KSTR(k-1) - r_2 \times KSTR(k-2) - r_3 \times KSTR(k-3)}{b_0} \quad (10)$$

[0058] The equation (10) (and the equations (4) and (5)) is obtained when the STR controller is designed on assumption that the dead time d of the engine 1 as a plant and the LAF sensor 17 as means for detecting the output from the plant is as long as three control cycles. However, due to a modification of the specifications of the engine 1 or the LAF sensor 17, in some cases, the dead time d can be longer than three control cycles. Assuming that the dead time $d = 5$ holds, for instance, the adaptive parameter vector $\hat{\theta}(k)$ and the input $\zeta(k)$ to the adaptive parameter-adjusting mecha-

nism are expressed by the following equations (11) and (12):

$$\hat{\theta}^T(k) = [b_0(k), r_1(k), r_2(k), r_3(k), r_4(k), r_5(k), s_0(k)] \quad (11)$$

$$\zeta^T(k) = [u(k), u(k-1), u(k-2), u(k-3), u(k-4), u(k-5), y(k)] \quad (12)$$

[0059] Further, the equation for calculating the adaptive control correction coefficient KSTR(k) is expressed by the following equation (13):

$$KSTR(k) = \frac{1}{b_0} \{ KCMD(k) - s_0 KACT(k) - r_1 KSTR(k-1) - r_2 KSTR(k-2) - r_3 KSTR(k-3) - r_4 KSTR(k-4) - r_5 KSTR(k-5) \} \quad (13)$$

[0060] Therefore, the amount of arithmetic operations required to calculate the adaptive control correction coefficient KSTR largely increases to such a level as will make it impractical to calculate the coefficient KSTR by using the CPU installed on the automotive vehicle for control of the engine. To eliminate this inconvenience, in the present embodiment, the configuration of the STR controller is adapted to the dead time $d = 3$ as shown in Fig. 5, and sampling timing (in the present embodiment, the operation cycle in which is calculated the input vector ζ used in the arithmetic operations is referred to as sampling timing) of the input vector ζ to the adaptive parameter-adjusting mechanism is set to a period corresponding to an actual dead time DACT ($DACT > d$, e.g. 5) (hereinafter referred to as "lowered-order STR"). More specifically, in the above equations (6) to (8), if $d = DACT = 3$ holds, $\zeta(k-d)$ is made equal to $\zeta(k-3)$, which is also the case with $\zeta^T(k-d)$, i.e. the transposed determinant of $\zeta(k-d)$, and the same applies to the following description. However, if the actual dead time DACT is larger than 3, e.g. equal to 5, the STR controller per se is adapted to $d = 3$, and the input vector $\zeta(k-d)$ of the equations (6) to (8) is set to $\zeta(k-5)$ which is adapted to the actual dead time DACT. Then, the adaptive parameter vector $\hat{\theta}(k)$ (which is composed of elements b_0, s_0, r_1, r_2 , and r_3 exclusive of r_4 and r_5) is applied to the equation (10) to calculate the adaptive control correction coefficient KSTR. In this case, the vector $\zeta(k)$ is expressed by the right side of the equation (5), which naturally corresponds to $d = 3$, and the orders of terms of the equation applied are not increased. The employment of the lowered-order STR makes it possible to carry out the adaptive control in a manner adapted to the actual dead time DACT without increasing the orders of terms of equations used in the STR controller and the adaptive parameter-adjusting mechanism, and hence carry out high-accuracy adaptive control while minimizing an increase in the amount of arithmetic operations required to obtain the adaptive control correction coefficient KSTR.

[0061] Figs. 6A and 6B show examples of changes in the adaptive correction coefficient KSTR and the actual equivalent ratio KACT which occurred when the desired equivalent ratio KCMD was changed in the case where the actual dead time DACT of the controlled object is longer than three control cycles. Fig. 6A shows a case in which the STR controller is adapted to the dead time $d = 3$, and the sampling timing of the input vector $\zeta^T(k)$ to the adaptive parameter-adjusting mechanism is also adapted to the dead time $d = 3$ by setting the factor $\zeta(k-d)$ in the equations (6) to (8) to $\zeta(k-3)$, while Fig. 6B shows a case in which the STR controller is adapted to the dead time $d = 3$, and the sampling timing of the input vector ζ to the adaptive parameter-adjusting mechanism is adapted to the dead time $d = 4$, which is substantially equal to the actual dead time DACT by setting the factor $\zeta(k-d)$ in the equations (6) to (8) to $\zeta(k-4)$. As is clear from these figures, even if the dead time d employed in designing the STR controller is shorter than the actual dead time DACT, it is possible to largely improve the responsiveness and stability of the adaptive control.

[0062] In general, the actual dead time of the controlled object is an analog value which changes continuously. However, in the adaptive control, the dead time has to be converted into a discrete or digital value. Therefore, assuming that the actual dead time is as long as 4.5 control cycles, for instance, it is preferable to select the more suitable one of values 4 and 5 for the dead time through comparison between control performance exhibited when the dead time DACT is set to 4 and that exhibited when the same is set to 5.

[0063] As described above, the employment of the lowered-order STR can enhance the performance of the adaptive control without increasing the amount of arithmetic operations. However, the model assumed in designing the control system is different from the actual object to be controlled, so that the adaptive parameter vector $\hat{\theta}$ can be liable to drift. Further, even if the lowering of orders of equations is not carried out, the equation (6) performs accumulation of slight identification errors caused by external disturbances in the adaptive parameter vector. Therefore, so long as the adaptive parameter vector $\hat{\theta}$ is calculated by using the equation (6), it is inevitable that the adaptive parameter vector $\hat{\theta}$ drifts when the engine continues to be in a steady operating condition.

[0064] To eliminate this inconvenience, in the present embodiment, means is additionally provided for preventing the adaptive parameter vector from drifting. This means will be described in detail hereinafter.

[0065] Fig. 7A shows an adaptive parameter vector-calculating section employed in the control system according to

the present embodiment, for calculating the adaptive parameter vector $\hat{\theta}$. In the figure, $\text{eid}(k)$ and $Q(k)$ represent the identification error and the variable gain, respectively, which are defined by the following equations (14) and (15), respectively:

$$\text{eid}(k) = D(Z^{-1})y(k) - \hat{\theta}^T(k-d)\zeta(k-d) \quad (14)$$

$$Q(k) = \frac{\Gamma(k-1)\zeta(k-d)}{1 + \zeta^T(k-d)\Gamma(k-1)\zeta(k-d)} \quad (15)$$

[0066] The identification error $\text{eid}(k)$ corresponds to the numerator of the identification error signal e^* (equation (8)), while the variable gain $Q(k)$ corresponds to a quotient obtained by dividing the second term of the equation (6) by the identification error $\text{eid}(k)$. When the identification error eid and the variable gain $Q(k)$ are used, the adaptive parameter vector $\hat{\theta}(k)$ is expressed by the following equation (16):

$$\hat{\theta}(k) = \hat{\theta}(k-1) + Q(k)\text{eid}(k) \quad (16)$$

[0067] As shown in Fig. 7A, the identification error $\text{eid}(k)$ is input to a nonlinear filter B51 and an output $\text{eida}(k)$ therefrom is input via a multiplier B52 to an integrator B53. The nonlinear filter B51 has an input/output characteristic e.g. as shown in Fig. 8A. More specifically, when $-\eta \leq \text{eid} \leq \eta$ holds (η represents a predetermined value empirically obtained), which means that eid falls within the deadzone defined by $-\eta$ and η , the output eida is set equal to 0 and when the identification error eid is outside the dead zone, the output eida is set equal to the input eid .

[0068] The arithmetic operations carried out at the blocks B52 and B53 correspond to those carried out by using the equation (16) in which $\text{eid}(k)$ is replaced by $\text{eida}(k)$.

[0069] In the present embodiment, the process of the nonlinear filter B51 is additionally carried out. As a result, when the engine enters a steady operating condition, and identification of the adaptive parameter vector $\hat{\theta}$ is substantially completed, the identification error eid falls within the dead zone defined between $-\eta$ and $+\eta$, so that the output eida from the block B51 is equal to 0, which prevents slight identification errors caused by differences in characteristics between the model assumed in designing the control system and the actual plant and external disturbances from being accumulated in the adaptive parameter vector $\hat{\theta}$, to thereby prevent drifting of the adaptive parameter vector $\hat{\theta}$.

[0070] The input/output characteristic of the nonlinear filter B51 shown in Fig. 8A shows a discontinuity as the input eid changes across $-\eta$, or η , which causes a drastic change in the vector $\hat{\theta}$ when the identification error eid goes beyond the dead zone. To eliminate this inconvenience, it is preferable that the nonlinear filter B51 has an input/output characteristic free from discontinuities as shown e.g. in Fig. 8B. That is, when $-\eta \leq \text{eid} \leq \eta$ holds, the output eida is set to 0, while when $\text{eid} > \eta$ holds, the same is set to $\text{eid} - \eta$, and when $\text{eid} < -\eta$ holds, the same is set to $\text{eid} + \eta$.

[0071] Further, the arrangement of Fig 7A in which the nonlinear filter B51 alone is added undergoes occurrence of a steady state error of the adaptive control (steady state difference between the desired equivalent ratio KCMD and the actual equivalent ratio KACT). This is because the identification error within the dead zone does not reflect on the adaptive parameter vector $\hat{\theta}$.

[0072] To overcome this inconvenience, it is desirable that blocks B61 to B66 are additionally provided, as shown in Fig. 7B. Multiplier B61, B64, an adder B62, and a delay B63 constitute a first-order lag filter (low-pass filter). The output eidf from this filter has its level limited by a limiting filter B65, and is added to the output eida from the nonlinear filter B51 by an adder B66. The output from the adder B66 is input to the multiplier B52.

[0073] The output eidf from the first-order lag filter eidf is expressed by the following equation (17):

$$\text{eidf} = \text{CLF} \times \text{eidfa}(k-1) + (1 - \text{CLF}) \times \text{eid}(k) \quad (17)$$

wherein CLF represents an averaging coefficient which is set to a value smaller than 1 but very close to 1, e.g. "0.988". In other words, the coefficient CLF is provided to set the cutoff frequency of the low-pass filter to a value close to 0.

[0074] The limiting filter 65 constitutes a limiter having a characteristic as shown in Fig. 8C. More specifically, when the output eidf from the first-order lag filter, which is input to this limiter, is smaller than $-\eta$, an output eidfa from the limiter is set to $-\eta$, whereas when the output eidf is larger than η , the output eidfa is set to η . When $-\eta \leq \text{eid} \leq \eta$ holds, eidfa is set to eidf .

[0075] In a variation shown in FIG. 7B, a steady state error component of the identification error eid is extracted by the low-pass filter having a cut-off frequency close to 0 and added to the output eida from the nonlinear filter B51. As a result, the steady state error component in the identification error eid is reflected on the adaptive parameter vector $\hat{\theta}$ to thereby reduce the steady state error of the adaptive control (steady state error between the desired equivalent ratio KCMD and the actual equivalent ratio KACT).

[0076] Further, the provision of the limiting filter B65 prevents the steady state error component of the identification error ϵ_{id} used for calculation of the adaptive parameter vector $\hat{\theta}$ from becoming larger than the original value due to the addition by the adder B66 when the identification error falls outside the dead zone (i.e. $\epsilon_{id} > \eta$ or $\epsilon_{id} < -\eta$).

[0077] Next, the equation for calculating the adaptive control correction coefficient KSTR actually employed in the present embodiment will be described. The above equations (5) to (10) are applied to a case where the control cycle and the repetition period of calculation of the KSTR value (repetition period of generation of TDC signal pulses) coincide with each other and the adaptive control correction coefficient KSTR thus calculated is commonly used for all the cylinders. In the present embodiment, however, the control cycle is as long as four TDC signal pulses corresponding to the number of cylinders, whereby the adaptive control correction coefficient KSTR is determined cylinder by cylinder. More specifically, the above-mentioned equations (5) to (10) are replaced by the following equations (18) to (23), respectively, to calculate the adaptive control correction coefficient KSTR cylinder by cylinder for use in the adaptive control:

$$\zeta^T(k) = [u(k), u(k-4), u(k-8), u(k-12), y(k)] \quad (18)$$

$$\hat{\theta}(k) = \hat{\theta}(k-4) + \Gamma(k-4) \zeta(k-4 \times d) e^*(k) \quad (19)$$

$$\Gamma(k) = \frac{1}{\lambda_1(k)} \left[\Gamma(k-4) - \frac{\lambda_2(k) \Gamma(k-4) \zeta(k-4 \times d) \zeta^T(k-4 \times d) \Gamma(k-4)}{\lambda_1(k) + \lambda_2(k) \zeta^T(k-4 \times d) \Gamma(k-4) \zeta(k-4 \times d)} \right] \quad (20)$$

$$e^*(k) = \frac{D(z^{-1})y(k) - \hat{\theta}^T(k-4) \zeta(k-4 \times d)}{1 + \zeta^T(k-4 \times d) \Gamma(k-4) \zeta(k-4 \times d)} \quad (21)$$

$$\lambda_3(k) = 1 - \frac{\|\Gamma(k-4) \zeta(k-4 \times d)\|^2}{\alpha + \zeta^T(k-4 \times d) \Gamma(k-4) \zeta(k-4 \times d)} \cdot \frac{1}{\text{tr} \Gamma(0)} \quad (22)$$

$$\text{KSTR}(k) = \{\text{KCMD}(k) - s_0 \times \text{KACT}(k) - r_1 \times \text{KSTR}(k-4) - r_2 \times \text{KSTR}(k-8) - r_3 \times \text{KSTR}(k-12)\} / b_0 \quad (23)$$

[0078] It should be noted that when the actual dead time DACT is e.g. 4, the adaptive parameters b_0 , s_0 , r_1 to r_3 are calculated by using the equations (19) to (22) with d set to 4.

[0079] Fig. 9 shows a subroutine for calculating the adaptive control correction coefficient KSTR which is executed at the step S9 in Fig. 3.

[0080] First, at a step S401, it is determined whether or not the reset flag FKLAFFRESET assumed "1" in the last loop. If FKLAFFRESET = "1" held in the last loop, which means that the adaptive control was not carried out in the last loop, the initialization of the adaptive parameters b_0 , s_0 and r_1 to r_3 is carried out by setting them to respective initial values, and then the program proceeds to a step S404. On the other hand, if it is determined at the step S401 that FKLAFFRESET = "1" held, which means that the adaptive control was carried out in the last loop as well, the process for calculating the adaptive parameters b_0 , s_0 and r_1 to r_3 is carried out by executing a routine shown in Fig. 10.

[0081] In the present embodiment, the calculation of $\hat{\theta}(k)$, i.e. adaptive parameters b_0 , s_0 and r_1 to r_3 by using the equation (19) is carried out once per four TDC periods (time period over which four TDC signal pulses are generated, i.e. one combustion cycle). Therefore, at a step S431 in Fig. 10, it is determined whether or not four TDC periods have elapsed from the last calculation of the adaptive parameters using the equation (19). If it is determined that four TDC periods have elapsed, the adaptive parameters $b_0(k)$, $s_0(k)$, and $r_1(k)$ to $r_3(k)$ are calculated by using the equation (19) at a step S432. If four TDC periods have not elapsed, the adaptive parameters b_0 , s_0 and r_1 to r_3 are set to respective immediately preceding values $b_0(k-1)$, $s_0(k-1)$, and $r_1(k-1)$ to $r_3(k-1)$.

[0082] After execution of the step S432 or S433, moving average values b_0AV , s_0AV , r_1AV , r_2AV , and r_3AV over p TDC periods (e.g. $p = 8$, i.e. 8 TDC periods) are calculated by using the following equations (24) to (28) at a step S434, followed by terminating the program. The control system includes a ring buffer (memory means) for storing values of the adaptive parameters b_0 , s_0 , r_1 to r_3 obtained over the p TDC periods (hereinafter p will be referred to as "the averaging period") to calculate the moving average values. The contents of the ring buffer are updated to newly-calculated adaptive parameter values or the immediately preceding values whenever one TDC period elapses, whereby the oldest data stored therein are erased. The updating of the contents of the ring buffer may be carried out by storing a newly calculated value of the adaptive parameter vector $\hat{\theta}$ over four TDC periods (i.e. by storing the newly calculated value $\hat{\theta}(k)$ as the values $\hat{\theta}(k)$ to $\hat{\theta}(k+3)$):

connected to said cylinders, including air-fuel ratio-detecting means arranged in said exhaust system for detecting an air-fuel ratio of a mixture supplied to said engine and for generating an output indicative of said air-fuel ratio of said mixture, an adaptive controller for determining an amount of fuel to be supplied to said engine with a first predetermined repetition period in a manner such that said output from said air-fuel ratio-detecting means becomes equal to a desired value, and adaptive parameter-adjusting means for adjusting adaptive parameters used by said adaptive controller,

the improvement wherein:

said adaptive parameter-adjusting means comprises:

adaptive parameter-calculating means for calculating said adaptive parameters with a second predetermined repetition period longer than said first predetermined repetition period and for generating output data indicative of results of said calculation; and

smoothing means for smoothing said output data from said adaptive parameter-calculating means and for generating output data indicative of the smoothed data with a repetition period at least equal to said first predetermined repetition period;

wherein said adaptive controller uses the smoothed data generated from said smoothing means as values of said adaptive parameters.

2. An air-fuel ratio control system according to claim 1, wherein said smoothing means stores said output data from said adaptive parameter-calculating means with said first predetermined repetition period, and carries out said smoothing by using a predetermined number of stored values of said output data from said adaptive parameter-calculating means.
3. An air-fuel ratio control system according to claim 2, wherein said smoothing comprises calculating moving average values of said output data from said adaptive parameter-calculating means.
4. An air-fuel ratio control system according to claim 3, wherein said adaptive parameter-calculating means includes storage means for sequentially storing values of each of said adaptive parameters with said first predetermined repetition period, and updating means for sequentially updating each of said values of said each of said adaptive parameters stored in said storage means to an identical value with said second predetermined repetition period, said smoothing means calculating moving average values of said values of said each of said adaptive parameters sequentially updated to said identical value.
5. An air-fuel ratio control system according to claim 2, wherein said smoothing means includes a ring buffer for storing said output data from said adaptive parameter-calculating means.
6. An air-fuel ratio control system according to claim 2, wherein said second predetermined repetition period is set to q times said first predetermined repetition period (q is an integer equal to or larger than 2), said predetermined number being equal to or larger than said q .
7. An air-fuel ratio control system according to claim 6, wherein said q depends upon a particular frequency.
8. An air-fuel ratio control system according to claim 3, wherein said second predetermined repetition period is set to q times said first predetermined repetition period (q is an integer equal to or larger than 2), said predetermined number being equal to or larger than said q .
9. An air-fuel ratio control system according to claim 2, wherein assuming that a number of said cylinders is j , said second predetermined repetition period is set to j times said first predetermined repetition period, said predetermined number being equal to t times said number j of said cylinders (t is an integer equal to or larger than 1).
10. An air-fuel ratio control system according to claim 3, wherein assuming that a number of said cylinders is j , said second predetermined repetition period is set to j times said first predetermined repetition period, said predetermined number being equal to t times said number j of said cylinders (t is an integer equal to or larger than 1).

FIG. 1

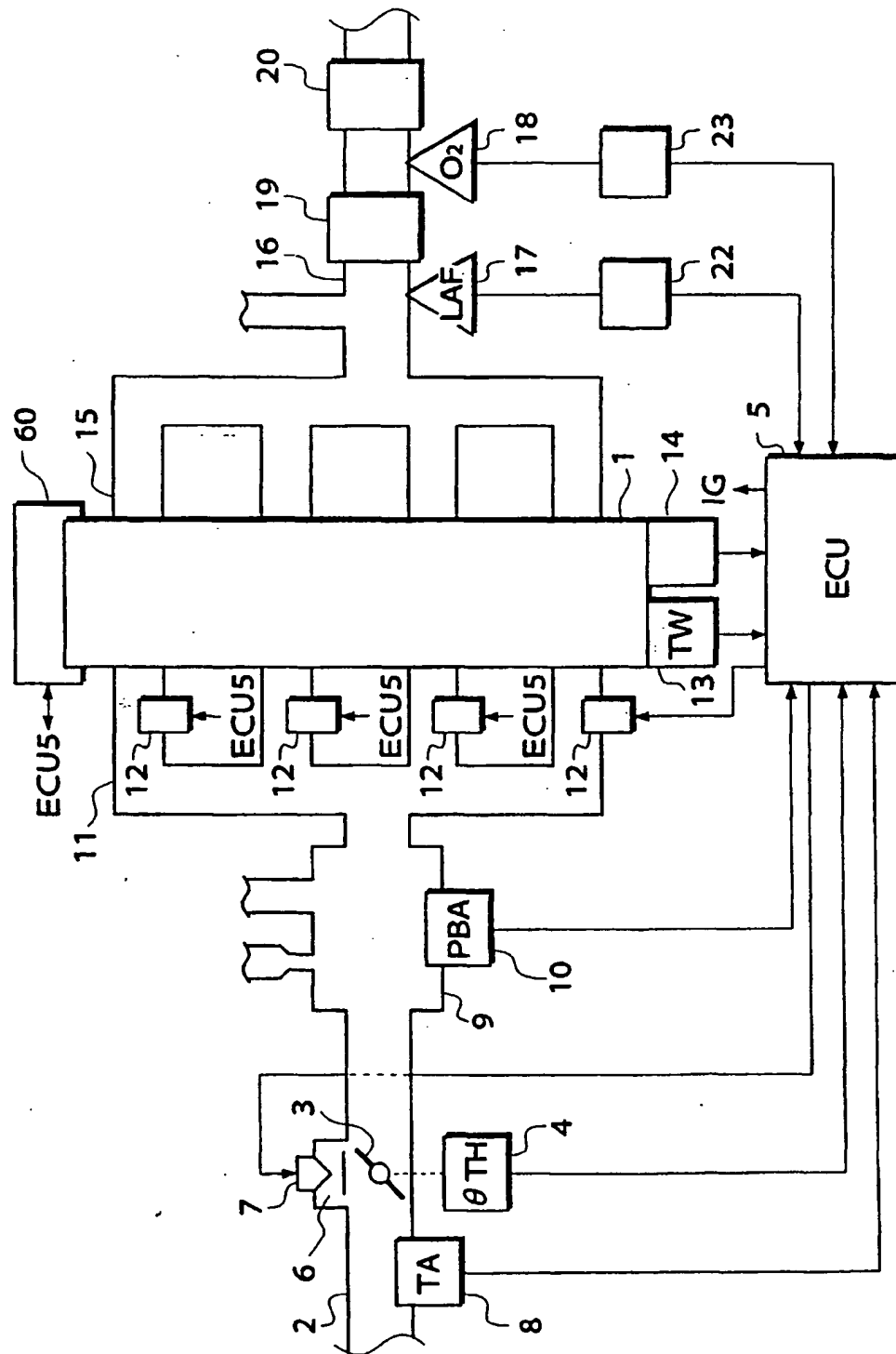


FIG. 2

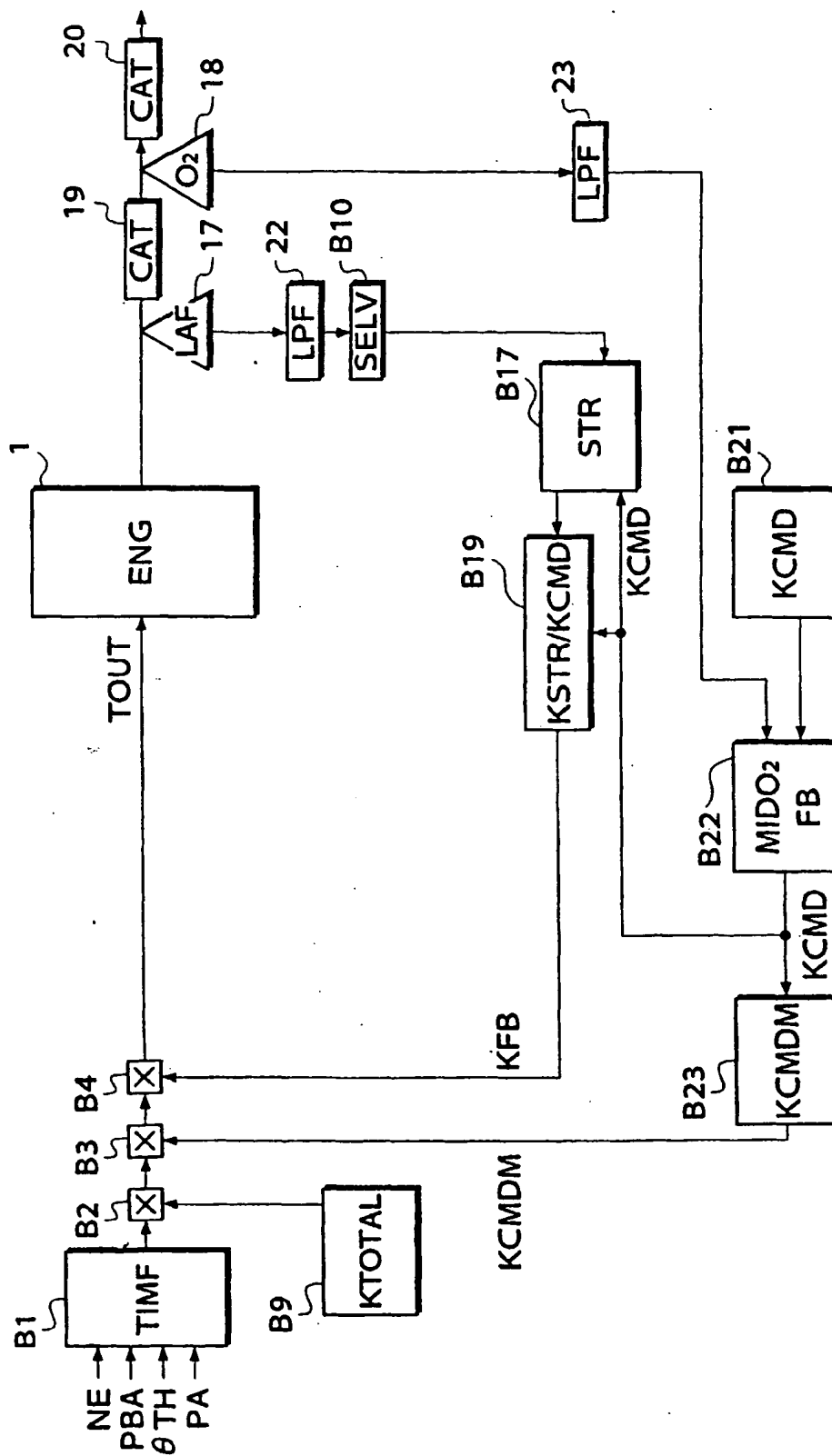


FIG.3

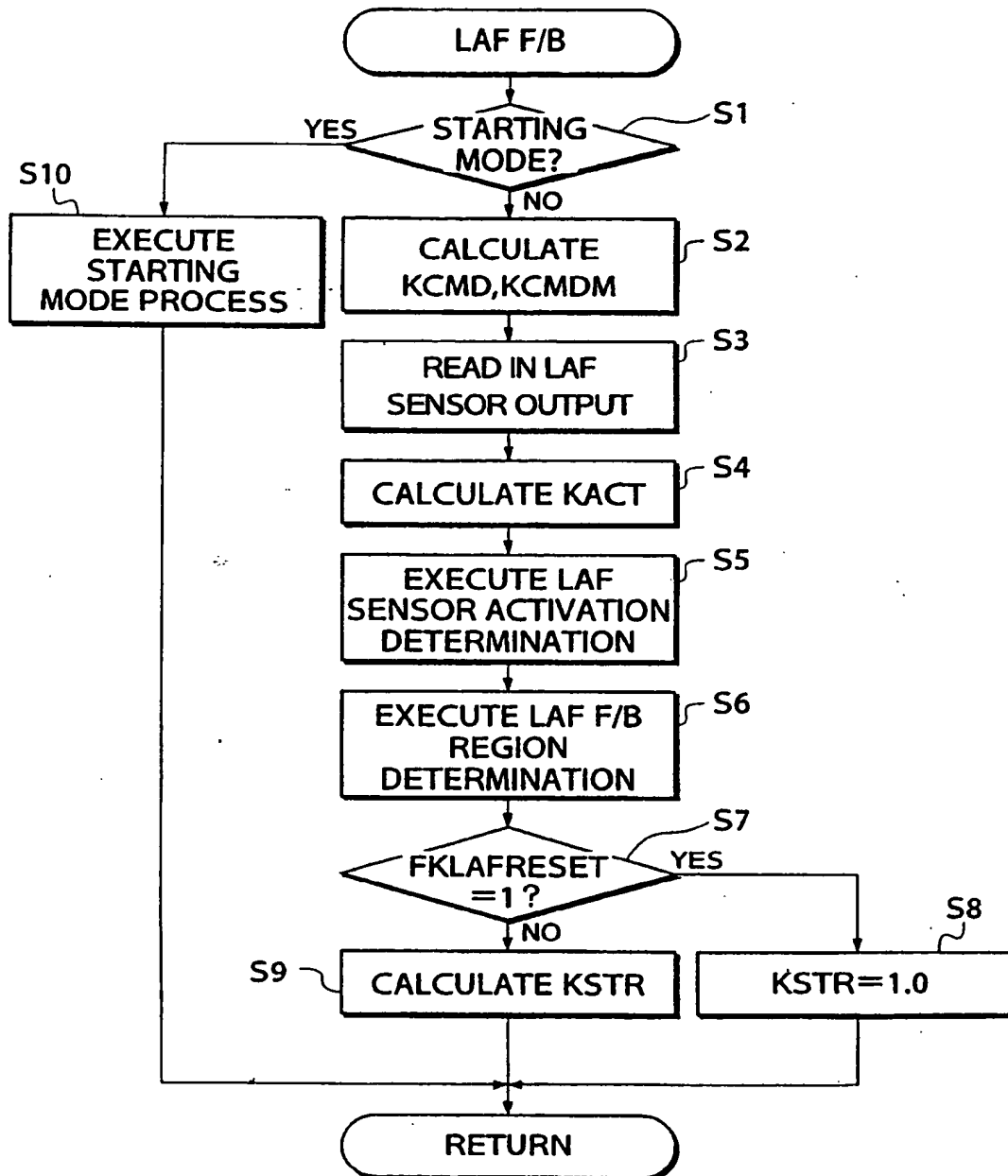


FIG.4

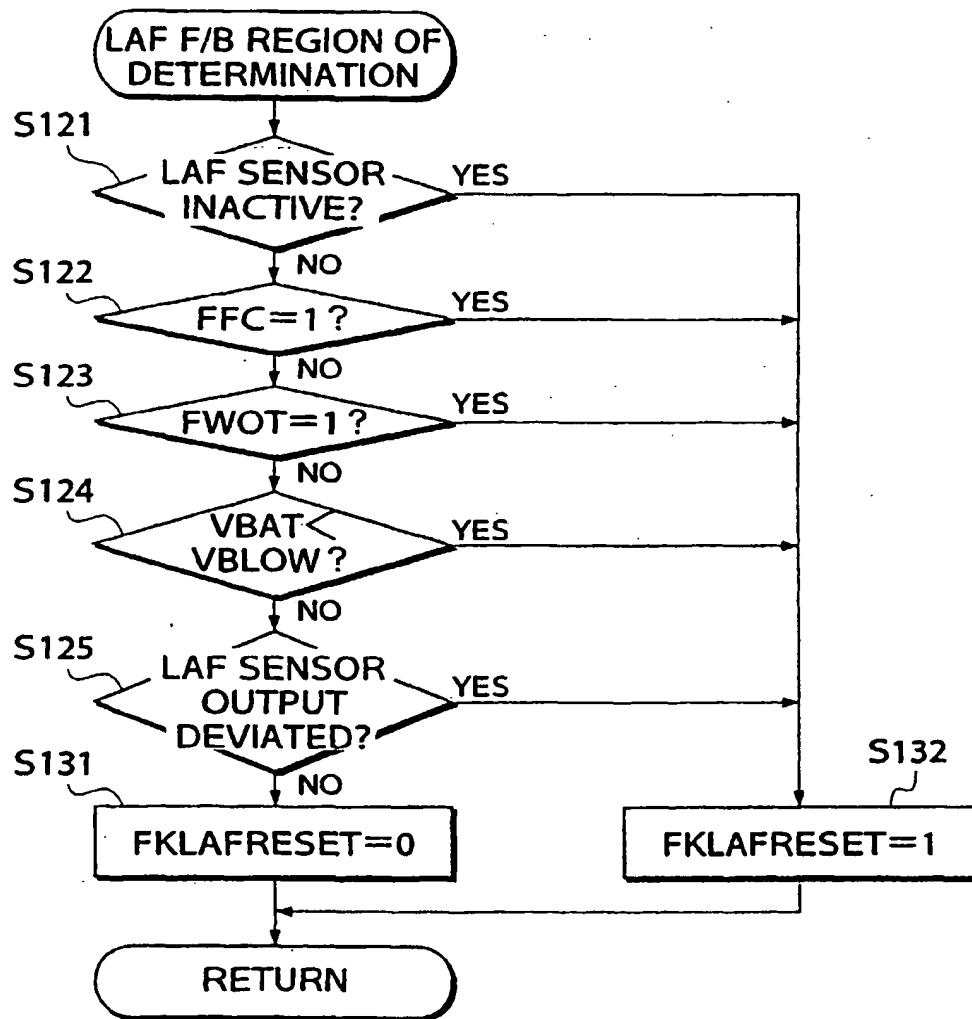


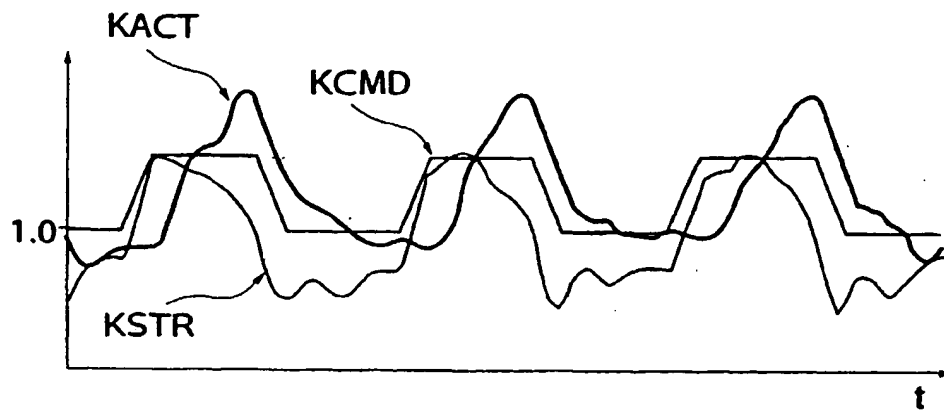
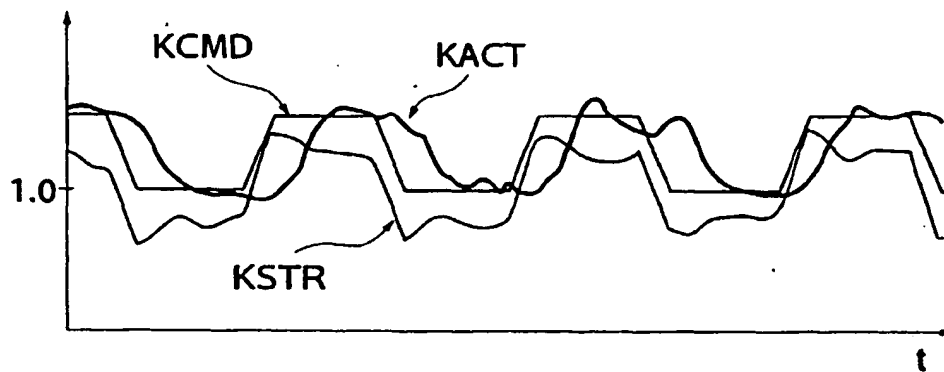
FIG.6A**FIG.6B**

FIG. 7A

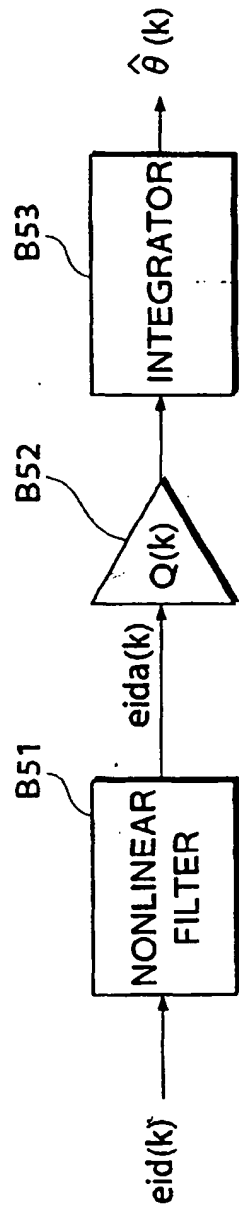


FIG. 7B

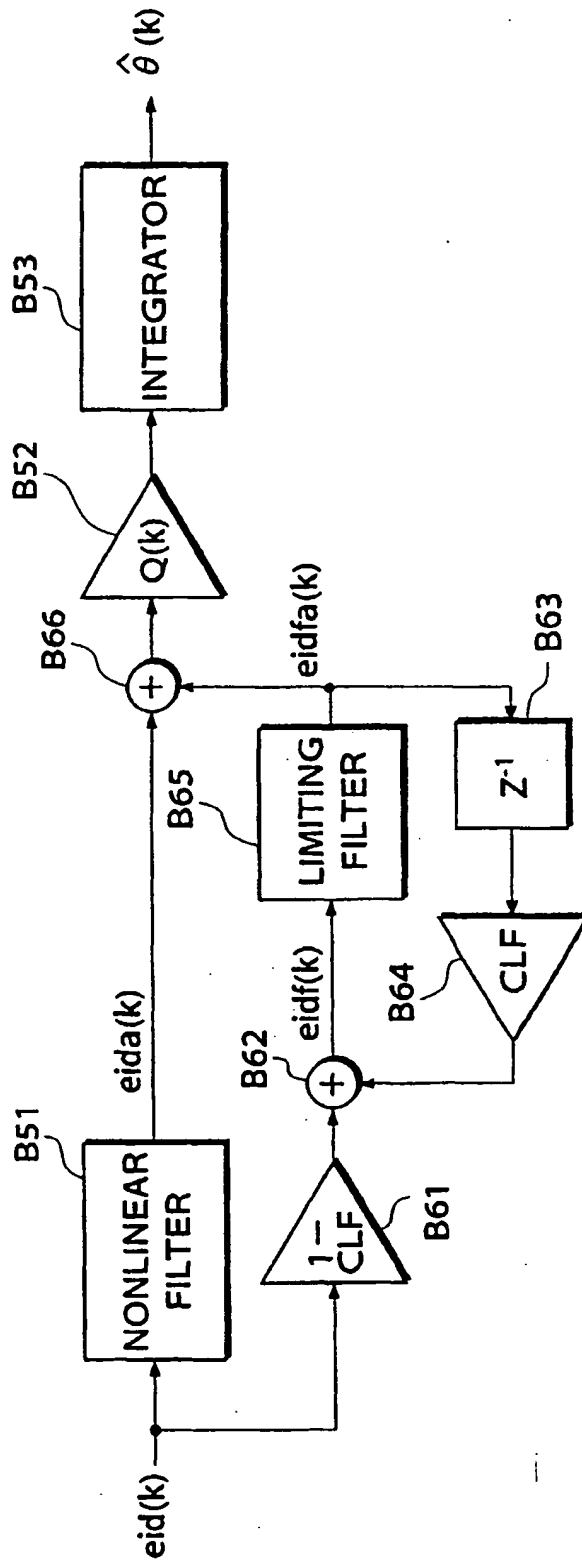


FIG.10

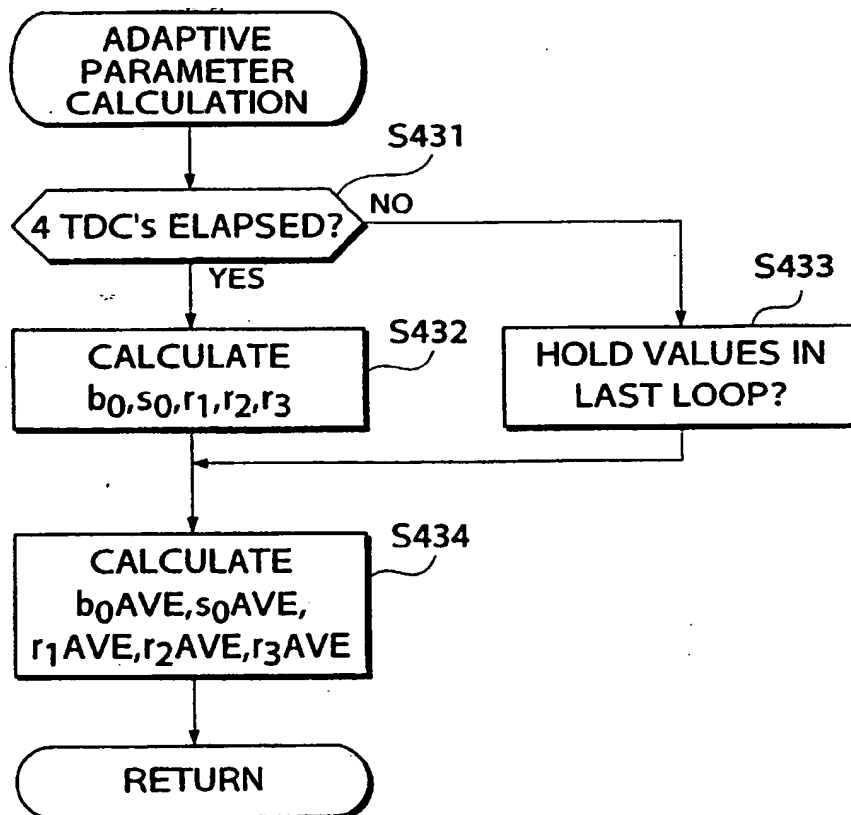


FIG.11

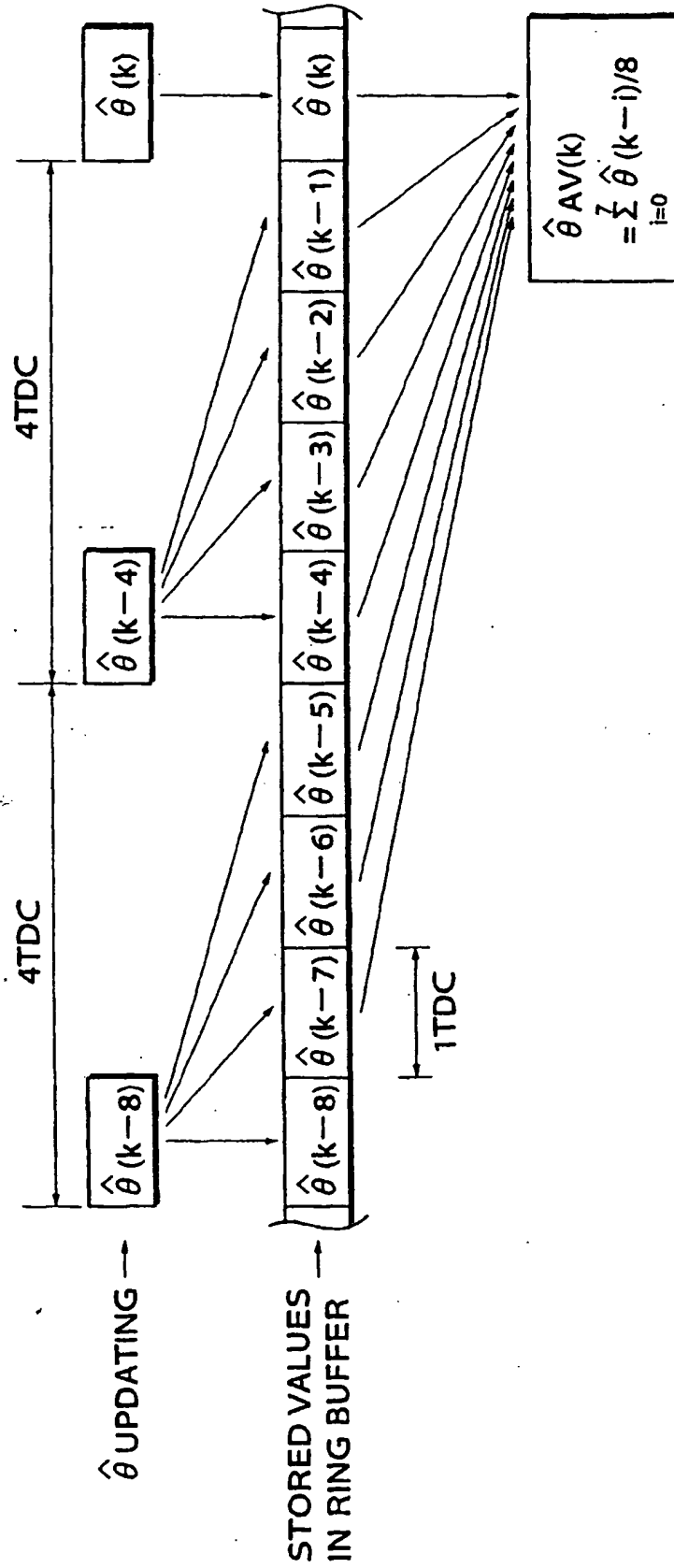
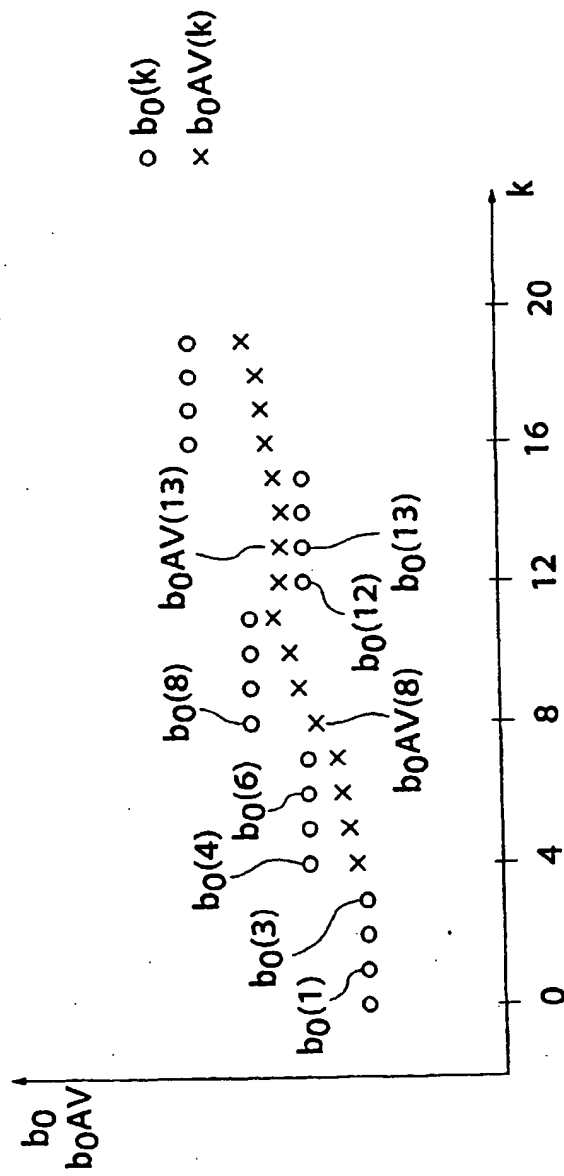


FIG. 12



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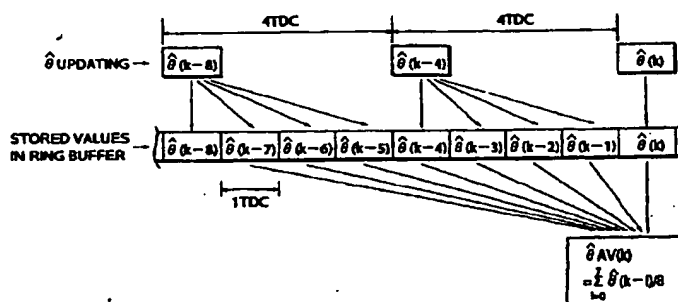
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(54) Air-fuel ratio control system for multi-cylinder internal combustion engines

(57) An air-fuel ratio control system for a multi-cylinder engine is provided. An air-fuel ratio sensor is arranged in an exhaust system of the engine for detecting an air-fuel ratio of a mixture supplied to the engine and for generating an output indicative of the air-fuel ratio of the mixture. An adaptive controller determines an amount of fuel to be supplied to the engine with a first predetermined repetition period in a manner such that the output from the air-fuel ratio sensor becomes equal to a desired value. An adaptive parameter-adjusting mechanism adjusts adaptive parameters used by the adaptive controller. In the adaptive parameter-adjusting

mechanism, the adaptive parameters are calculated with a second predetermined repetition period longer than the first predetermined repetition period, and output data indicative of results of the calculation is generated. Further, the output data indicative of results of the calculation is smoothed and output data indicative of the smoothed data is generated with a repetition period at least equal to the first predetermined repetition period. The adaptive controller uses the smoothed data as values of the adaptive parameters.

FIG.11



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Application Number
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Place of search THE HAGUE		Date of completion of the search 30 May 2000	Examiner De Vita, D
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